The local dark matter distribution in self-interacting dark matter halos

Based on the paper: E. Rahimi, E. Vienneau, N. Bozorgnia, A. Robertson, *JCAP* 02 (2023) 040

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June 2023

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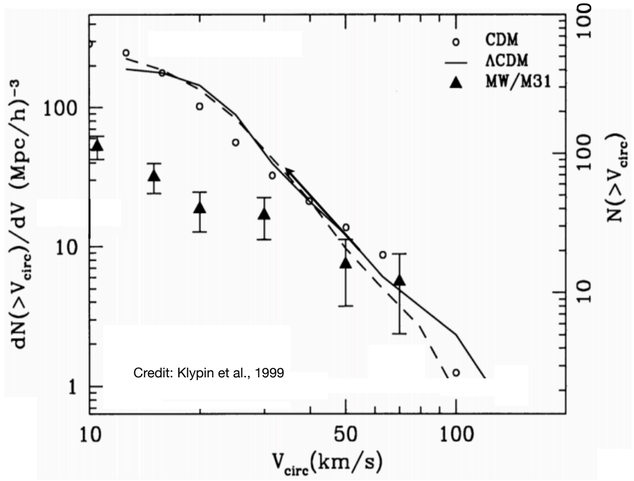

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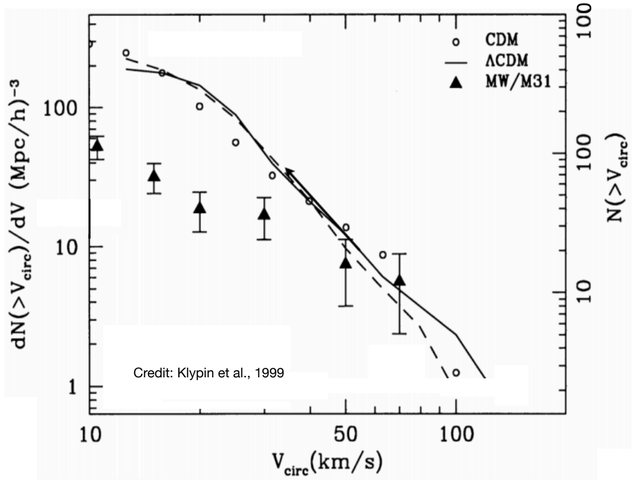
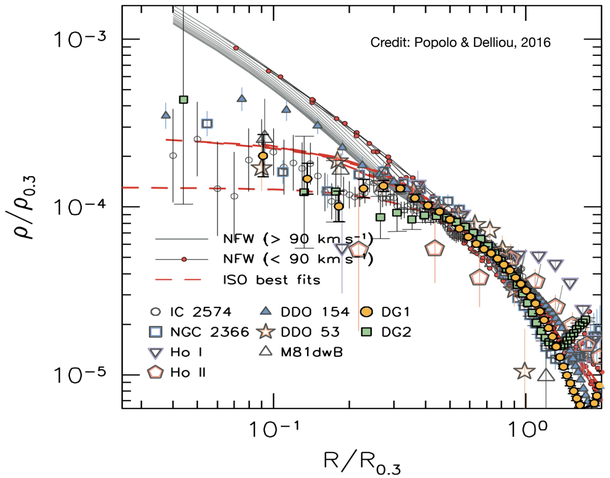


Core-cusp



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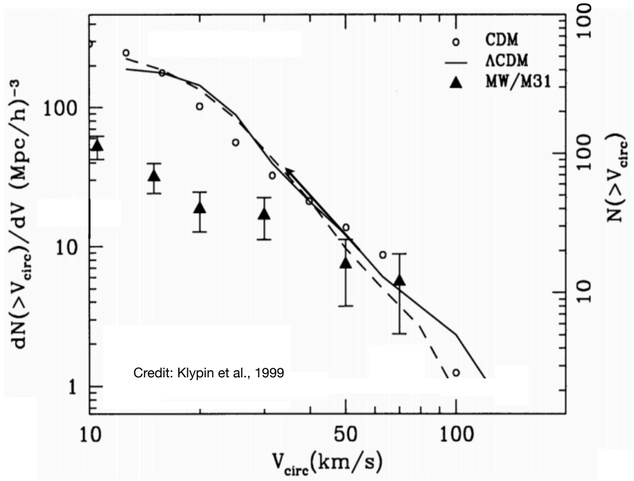

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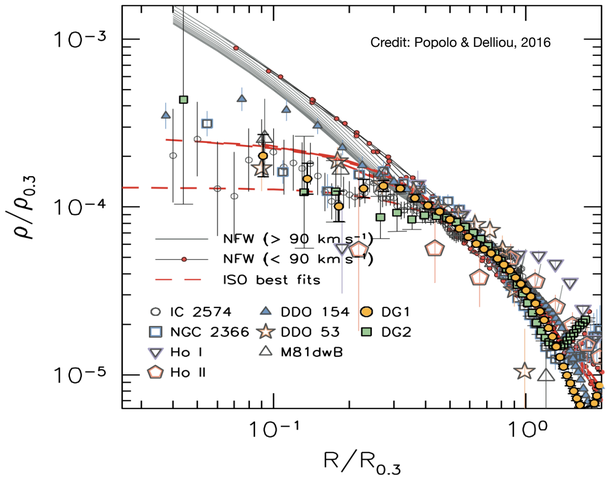
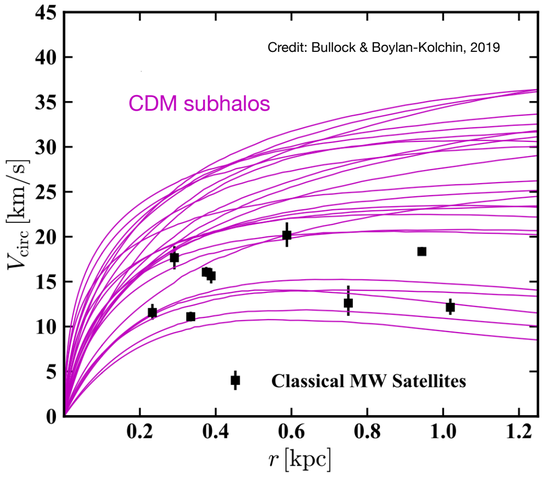


Too Big to Fail



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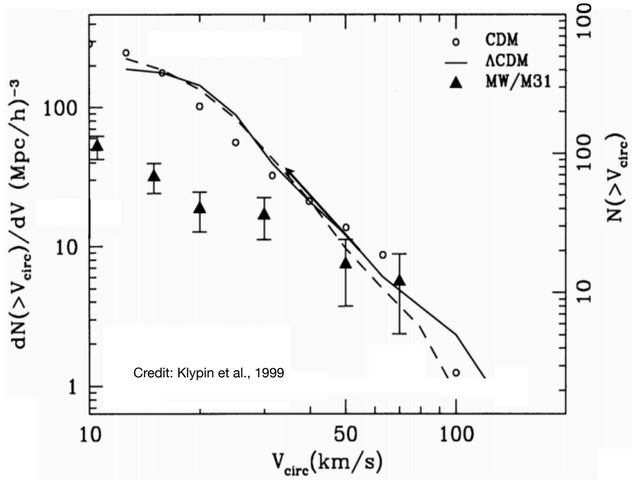

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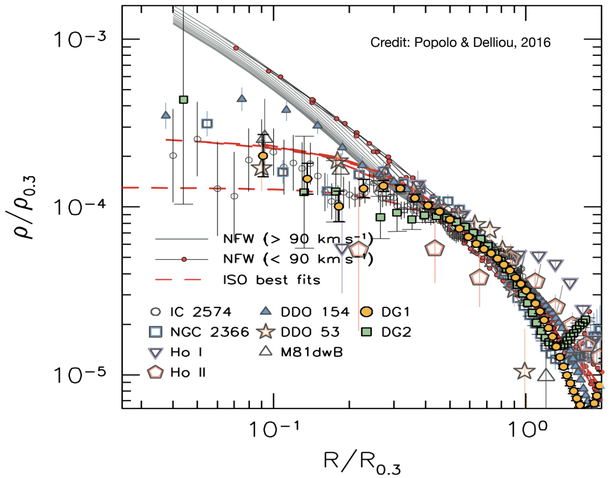

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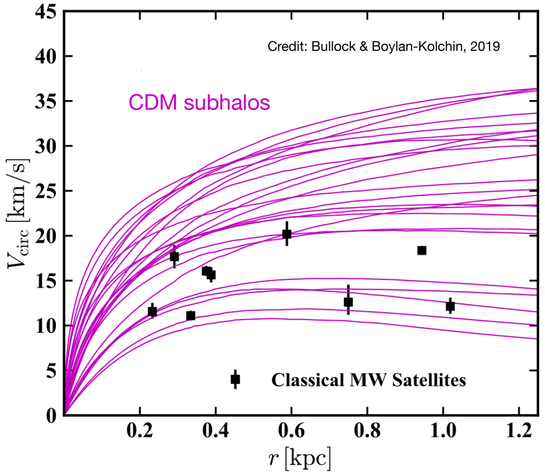

- Possible solutions: improved observations , baryonic physics , alternative DM model
- One simple alternative to CDM is **self-interacting dark matter (SIDM)**
- We are interested in the impact that the presence of baryons *and* DM self-interactions has on direct detection

Direct detection astrophysical uncertainties

$$\frac{dR}{dE_R} = \frac{A^2 \sigma F^2(E_R)}{2 m_\chi \mu_{\chi p}^2} \rho_\chi \int_{v>v_{min}} d^3v \frac{f_{det}(\mathbf{v}, t)}{v}$$

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- ρ_χ , local dark matter density
- $f_{gal}(\mathbf{v},t)$, galactic frame velocity distribution
- $\eta(v_{min},t) = \int_{v<v_{min}} d^3v \frac{f_{det}(\mathbf{v},t)}{v}$, halo integral

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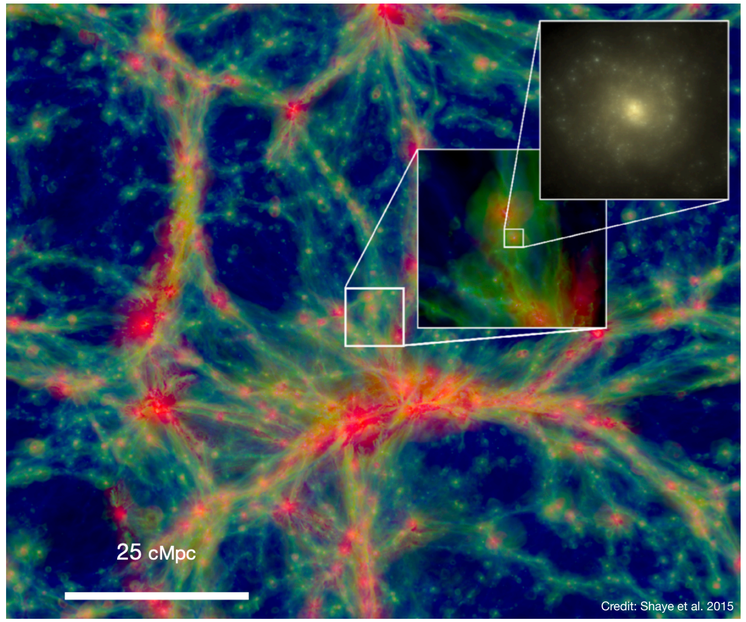
- Historically, direct detection analyses assume the **Standard Halo Model (SHM)**
  - Isothermal sphere with asymptotically flat rotation curve
  - Truncated Maxwellian velocity distribution
  - ρ_χ = 0.3 - 0.4 GeV/cm^3
  - v_{peak} = 230 km/s
  - v_{esc} = 544 km/s
- Does the SHM remain a good assumption for SIDM?

Hydrodynamical simulations of SIDM

- EAGLE-50
  (**E**volution and **A**ssembly of **G**a**L**axies and their **E**nvironment)
  - Box size: 50 Mpc^3
  - Gravity treatment: Tree particle mesh
  - Hydrodynamics treatment: Smooth particle hydrodynamics
  - Mass/spatial resolution: $\sim 10^6\ \mathrm{M}_\odot/10^0$ kpc



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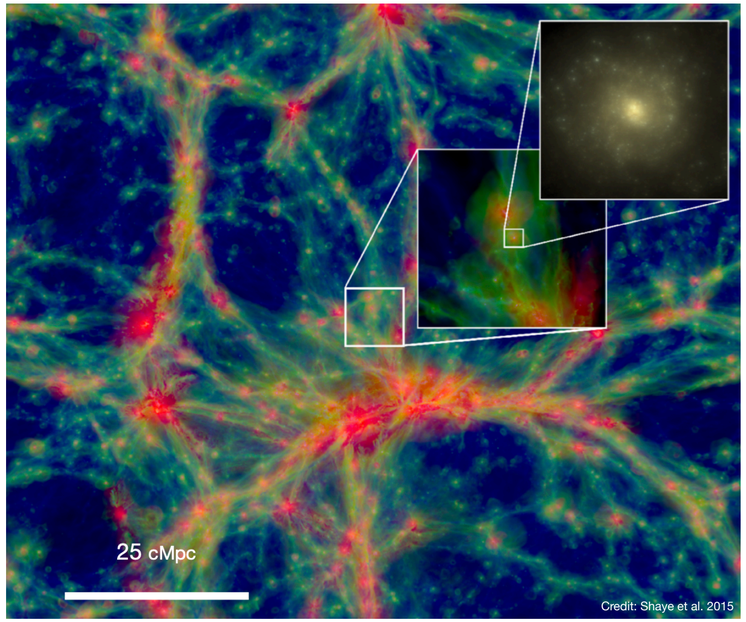
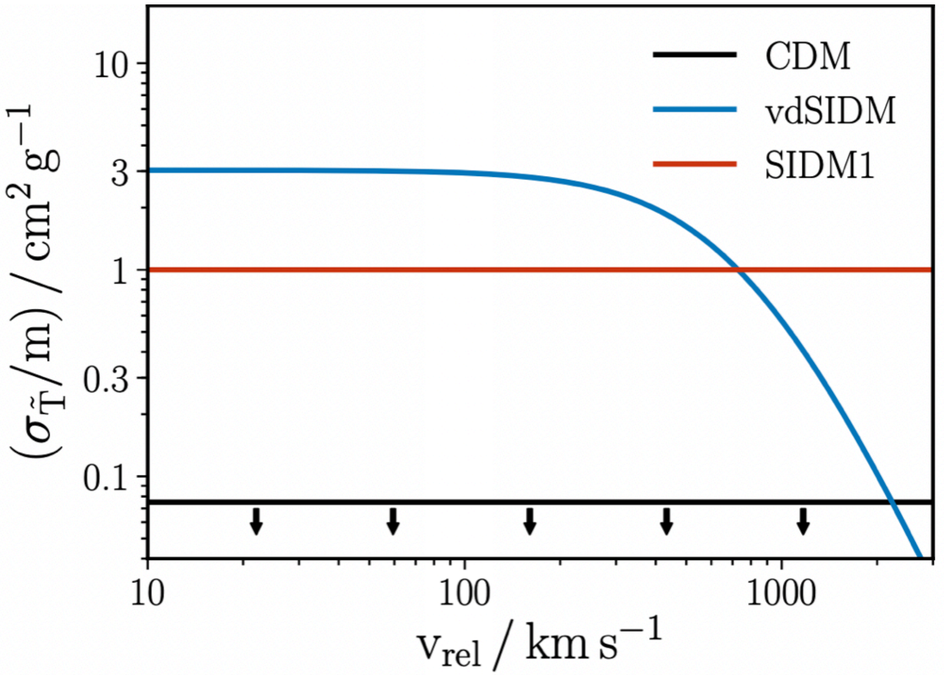
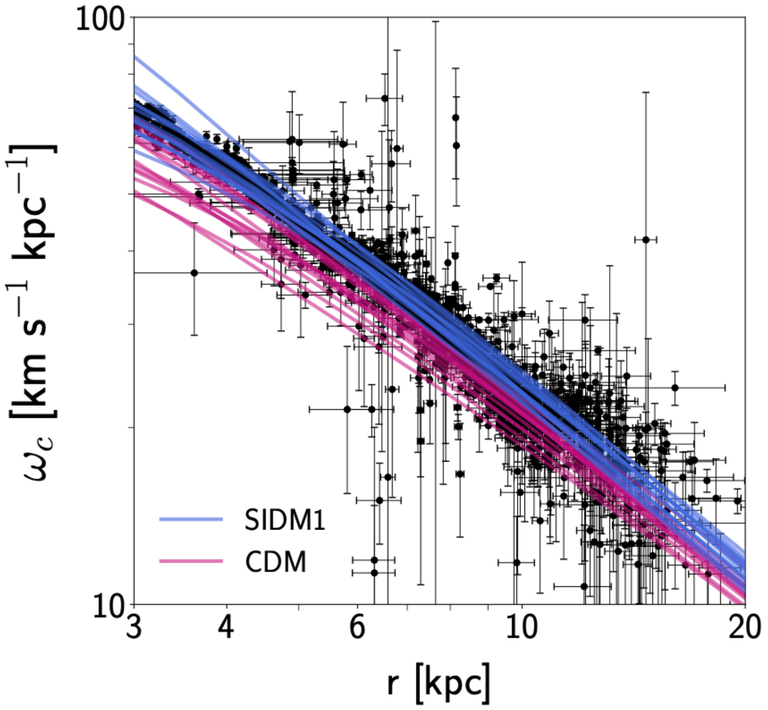


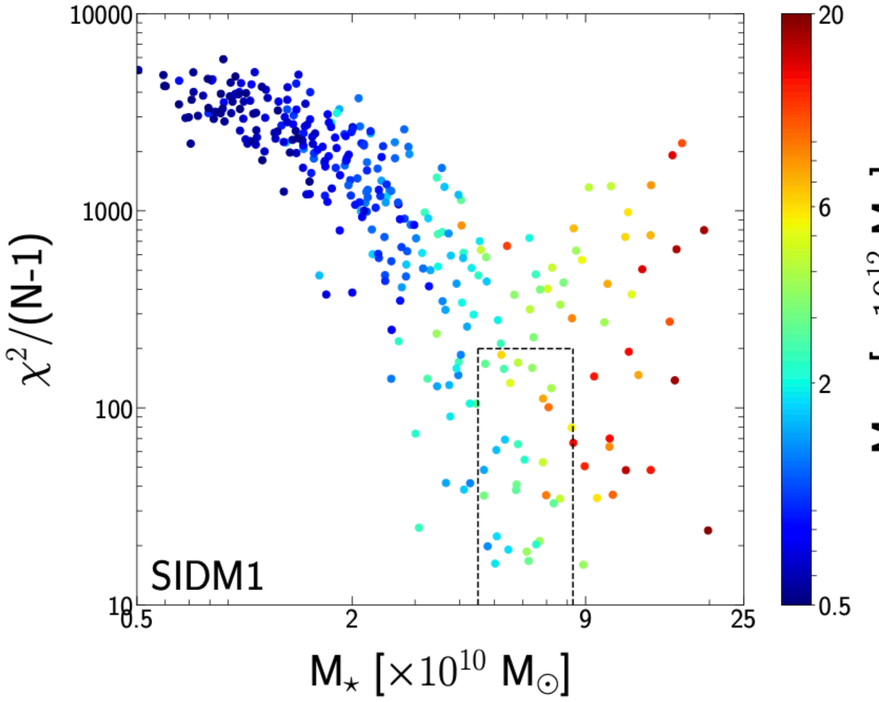
- SIDM implementation **[Robertson et al. 2021]**
  - Nearby DM particles randomly interact at each time step
  - Constant (SIDM1) and velocity-dependent (vdSIDM) cross-sections



Milky Way analogues

- Selection criteria
  - Virial mass in the range $[0.5 - 3] \times 10^{12}\ M_\odot$
  - Stellar mass in the range $[4.5 - 8.3] \times 10^{10}\ M_\odot$
  - Rotation curve agrees with observations
    [Iocco, Pato & Bertone, 2015]
  - Relaxed halo no overly significant substructure

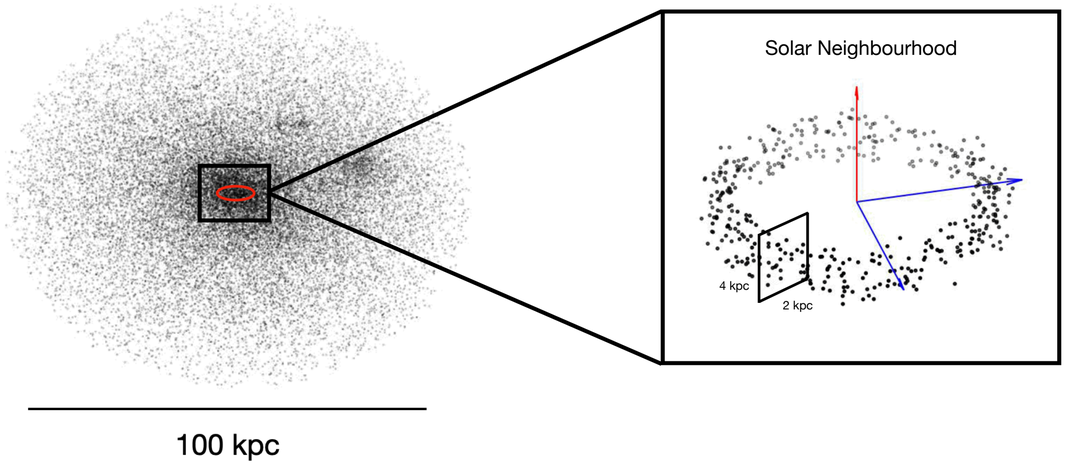




- 14 SIDM1 and 17 vdSIDM halos

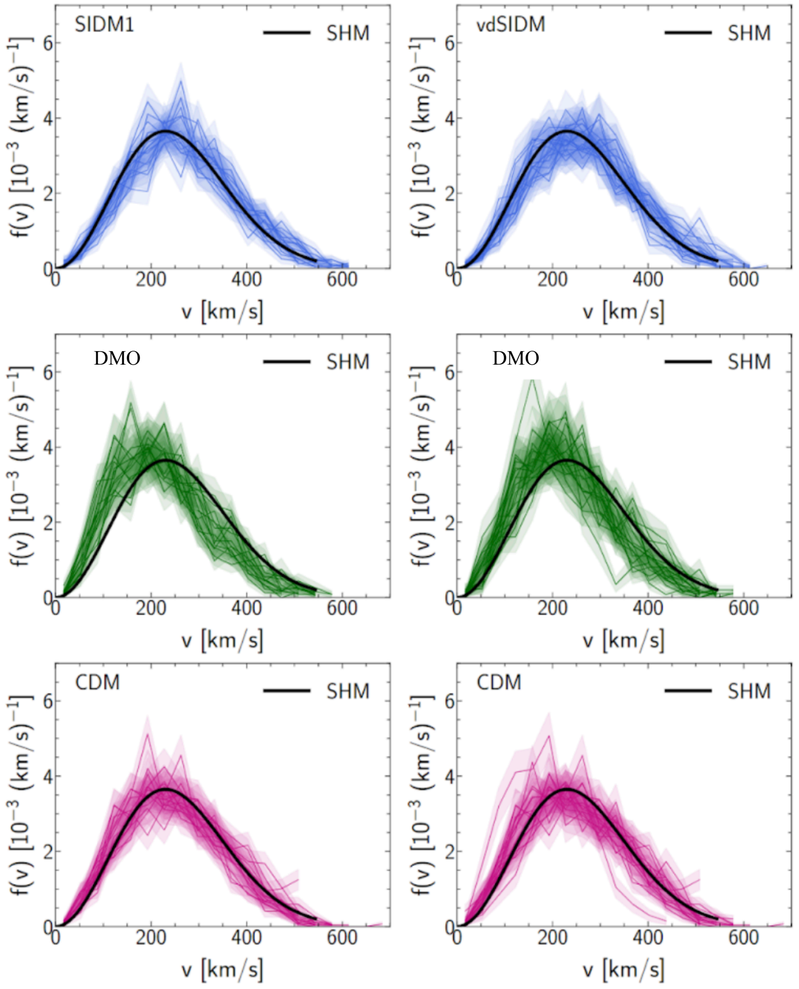
Local dark matter density

- CDM and SIDM values agree with the fiducial SHM value, with global/local estimates from observations and with previous CDM simulations
- DMO halos have lower DM density due to lack of baryonic contraction
- DM self interactions have no significant impact on ρ_χ

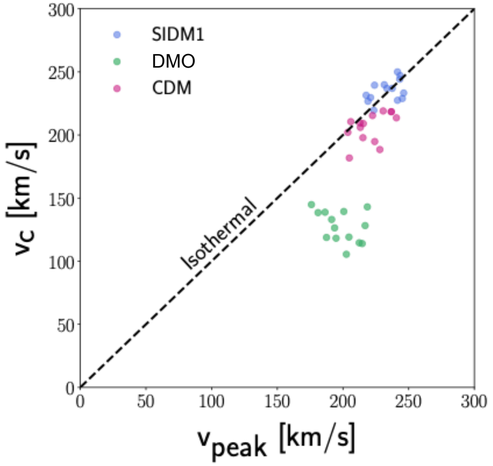


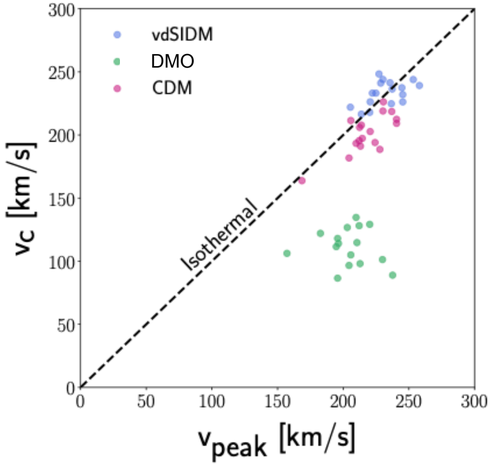
	DM particles	Local DM density [GeV/cm^3]	DM density variation %
SIDM1	$447 - 717$	$0.41 - 0.66$	$4 - 26$
DMO	$274 - 544$	$0.30 - 0.59$	$4 - 53$
CDM	$380 - 729$	$0.35 - 0.67$	$4 - 41$
vdSIDM	$325 - 734$	$0.30 - 0.67$	$5 - 39$
DMO	$216 - 496$	$0.23 - 0.54$	$15 - 54$
CDM	$373 - 729$	$0.34 - 0.67$	$4 - 41$

Local Galactic frame velocity distributions



- CDM and SIDM models agree well with SHM
- Baryonic contraction leads to higher peak speeds
- Baryons have a more significant effect compared to DM self-interactions



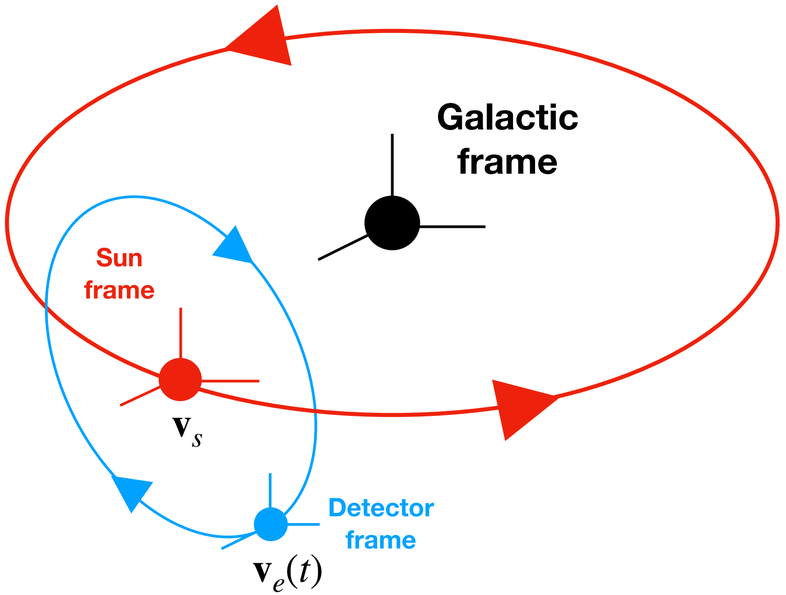


- SHM model

$$f(v) = \frac{4\,v^2}{\sqrt{\pi} v_0^3} \exp\left(-\frac{v^2}{v_0^2}\right)$$

$$v_0 = v_{\text{peak}} = 230 \text{ km/s}$$

Time averaged halo integrals



$$\eta(v_{\rm min}, t) = \int_{v>v_{\rm min}} d^3v \, \frac{\tilde{f}_{\rm det}(\mathbf{v}, t)}{v}$$

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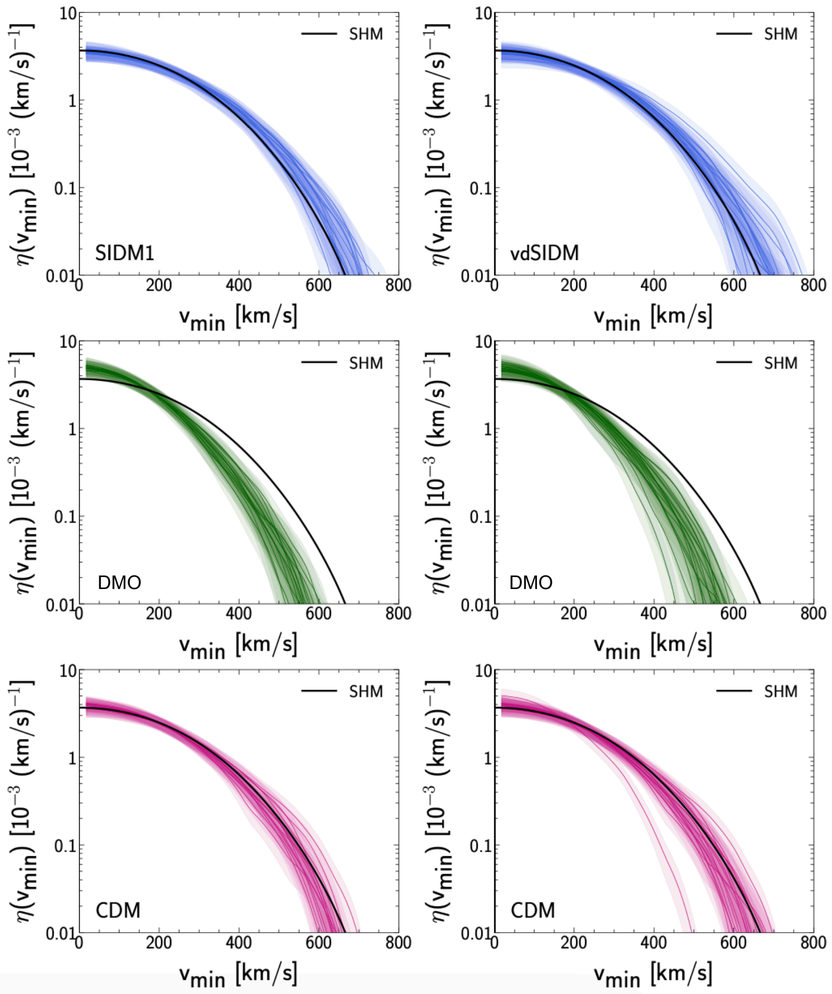

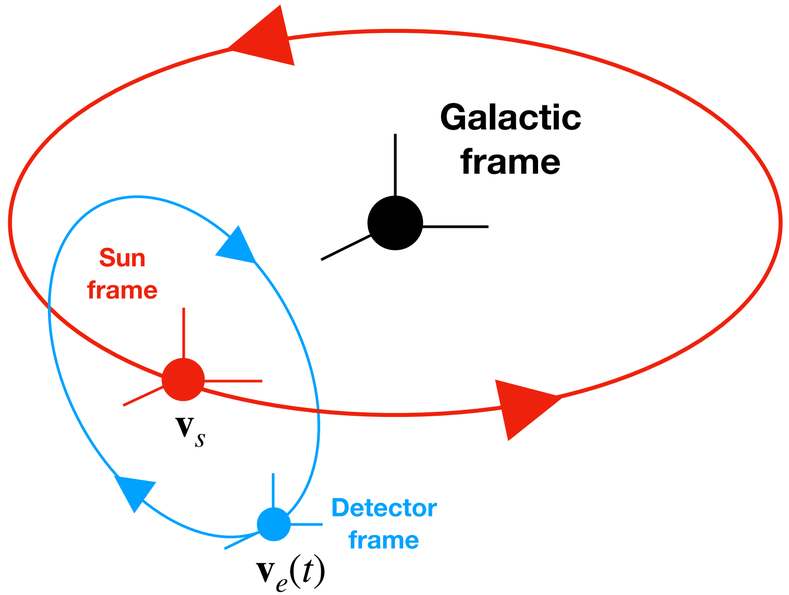

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- CDM and SIDM agree well with SHM halo integral
- The presence of baryons and DM self-interactions result in small shifts of halo integral tails to higher velocity
- Largest astrophysical uncertainty in exclusion limits are for light DM candidates

Summary

- We have found that the presence of DM self-interactions in hydrodynamical simulations does not have a significant effect on the local DM distribution compared to CDM
- The presence of baryons has a more significant effect on the local distribution compared to DM self-interactions
- Additional considerations and results:
  - Choice of “Solar neighbourhood” → Our results are robust to different sized torii
  - Velocity distribution components → Generally, the local DM has noticeably larger speeds in the azimuthal direction for CDM and SIDM halos, compared to DMO
  - Galaxy morphology → Local DM density is larger for halos with more prominent disks
- Analysis can be applied to other simulations and additional alternative DM models (WDM, FDM, etc.)

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Thank you!

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Backups

Cold Dark Matter

- Observational evidence
  - Spiral and elliptical galaxy systematics
  - Cluster mass measurements
  - Structure formation
  - CMB power spectrum
  - …..and much more
- Suggests the existence of matter that is
  - **Massive**
  - **Non-relativistic**
  - **Stable**
- CDM is a model of particles which are characterized as having
  - **Formed when non-relativistic**
  - **Very weak non-gravitational interactions**
- CDM candidates include **WIMPs**, **axions** and **MaCHOs**
- Large-volume dark matter-only CDM simulations agree with observations on Mpc scales but tension arises on kpc scales :
  - **Missing satellites** - CDM predicts too many satellites
  - **Core-cusp** - CDM predicts cusps
  - **Too Big To Fail** - CDM predicts too massive satellites
- Thus alternatives to CDM are explored …

$$f(v_i) = \frac{N_i}{\Delta v \; N_T}$$